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CAMBRIDGE ACOUSTICAL ASSOCIATES, INC.

RESEARCH, DEVELOPMENT AND CONSULTING IN ENGINEERING AND SCIENCE

DESIGN PARAMETERS OF FREE-FLOODING CYLINDRICAL TRANSDUCERS

Miguel C. Junger

February 1969

Technical Report U-308-210
Prepared for Office of Naval Research
Acoustics Programs - Code 468
Contract N-00014-69-C-0096
NR 185-301/5-21-68(468)

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Abstract

The free-flooding cylindrical transducer devoid of pressure-release material combines resistance to hydrostatic pressure with design flexibility resulting from the existence of resonances primarily controlled by two independent dimensions: the radius, which controls the structural (ring) resonance, and the axial length which determines the acoustic ("squirter") resonance. Values of radiation impedance generated for a squirter of vanishing wall thickness from an integral equation formulation of the free-flooding cylinder of finite length, were used to compute curves of dimensionless natural frequency vs. squirter aspect ratio (ratio of length to diameter) and of motional conductance vs. dimensionless frequency. It is concluded that (a) squirters of small aspect ratio are undesirable, (b) squirters of medium and large aspect ratio can combine wide bandwidths with substantial conductance levels; (c) squirters with large aspect ratios should have *in vacuo* natural frequencies substantially lower than generally obtained with transducer materials; the natural frequency can be lowered to the desired value by attaching axially oriented inertia wedges to the squirter; (d) near-coincidence of the acoustical (squirter) resonance with the structural (ring) resonance can produce an exceptionally wide bandwidth for squirters of large aspect ratio provided the slopes of the transducer and radiation reactances mutually compensate near the *in vacuo* natural frequency, thus producing a frequency range of near-resonant condition. An equation is derived which the transducer parameters must satisfy to produce this condition.

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List of Symbols

A	area of shell = $4\pi aL$
a	mean radius of free-flooding cylindrical shell
c	sound velocity in water
c_t	effective bar velocity of transducer material
E	Young's modulus of transducer material
h	thickness of shell
k	acoustic wave number, ω/c
$(ka)_n$	dimensionless natural frequency of ring resonance of submerged transducer
$(ka)_r$	dimensionless squirter resonance at which peak radiation resistance occurs
L	half-length of shell
R_r	radiation resistance
X_r	radiation reactance
X_t	mechanical reactance of transducer in vacuo
Z	combined mechanical and radiation impedance of submerged transducer
Z_r	radiation impedance
Z_t	mechanical impedance of transducer in vacuo
θ	acoustic resistance
θ_t	effective resistance ratio associated with structural losses
ρ	density of water
ρ_t	effective density of transducer material
χ	acoustic reactance ratio
ω	circular frequency
ω_{nv}, ω_n	circular natural frequency of radial shell mode in vacuo and submerged, respectively

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I. ADVANTAGES OF THE "SQUIRTER" CONCEPT

A. Deep Submergence

Sonar transducers arranged in a planar array are usually decoupled from the fluid medium along a boundary parallel to their radiating surface. This decoupling is achieved by an air cavity or a coating of "pressure-release" material. Alternatively, the transducer material may form a shell enclosing an air cavity. The result is a structure whose operating depth is limited by its ability to withstand hydrostatic pressure without collapsing. Because it is frequently advantageous to operate a sonar transducer in or below the SOFAR channel, a source configuration effectively impervious to hydrostatic pressure presents great practical advantages. The free-flooding, radially vibrating cylindrical shell or squirter, devoid of any pressure-release lining, exemplifies such a configuration.

B. Design Flexibility

Conventional transducers display a single natural frequency of significance within their operating frequency range. The mass-like acoustic radiation loading shifts this natural frequency below its *in vacuo* value. In contrast, the radiation loading of a free-flooding cylinder can be stiffness-like, thus raising the natural frequency above its *in vacuo* values. Of greater practical importance is the existence of two resonances, one primarily structural and the other primarily acoustical. Limiting our calculations to a cylinder whose half-length L does not exceed 1.2 times its radius a, this structural resonance is associated with radial ring modes whose frequency is determined primarily by a, and by the bar velocity c_t of the transducer material. The acoustical resonance is associated with a longitudinal vibration of the liquid column and is determined primarily by the length 2L and the sound velocity c of water. The respective location of these two resonances can be adjusted by varying the aspect ratio L/a. The relative magnitude of these two natural frequencies will be shown to determine the bandwidth and power level of the transducer. In summary, the existence of two resonances each depending on a different transducer dimension provides an unusual degree of flexibility in designing a transducer for given specifications.

II. REVIEW OF SQUIRTER STUDIES

A. Summary of Experimental and Early Analytical Studies

The squirter concept has been the subject of extensive experimentation and development work. In fact, the largest single sonar transducer reported in the literature is a magnetostrictive (nickel-cobalt) squirter of 12 ft diameter ($L/a \approx 1/13$) containing over 5 tons of transducer material, built by the Bendix Corporation. The remarkable reliability of the magnetostrictive squirter devoid of pressure-release material makes it suitable for long-term unattended operation at great depth. A successful example of such a system is the SNAP-7E atomically powered squirter moored at a depth of 2000 fathoms. These and other developments in the area of magnetostrictive squirters through 1966 are described in a review paper by Bulmer, Meyers and Parssinen.[1] Experimental studies have been performed on magnetostrictive squirters at the USN Underwater Sound Laboratory,[1] and the U.S. Naval Research Laboratory,[2] and on ceramic squirters at the U.S. Navy Electronics Laboratory,[3] now the U.S. Navy Undersea Warfare Center, and at Canada's Defence Research Establishment Atlantic.[4]

In spite of this significant experimental and development effort an analytical basis for designing free-flooding transducers devoid of pressure-release material has not been available until recently. The earliest analysis of the squirter is due to Robey,[5] who considered a free-flooding cylindrical shell radiating from its open ends which were surrounded by infinite plane baffles, thus eliminating radiation loading on the outer surface of the squirter. The radiation loading on this outer surface can be approximated by a solution also derived by Robey[6] for a radially pulsating cylinder extended by two semi-infinite rigid cylindrical baffles. The mathematical model thus evolved can not account for the acoustical interaction between the inner and outer squirter surfaces. More recently the radiation loading has been approximated in terms of spheroidal[7] and toroidal[8] wave harmonics.

B. The Present Study

This study utilizes numerical results generated by Mary Duncan and her coworkers[9] from an integral equation formulation of the radiation loading on a squirter of vanishing wall thickness.[10] The integral equation is constructed by combining the solution for the sound field outside an infinite cylinder

excited over a finite length,[6] and the equivalent solution for the sound field inside this same cylinder.[11] The radial velocity over the length of the squirter, on the surface defined in cylindrical coordinates as $r=a$, $-L < z < L$, is prescribed and equal to a constant, U. The radial velocity distribution over two semi-infinite cylinders extending the squirter ($r=a$, $-\infty < z < -L$ and $L < z < \infty$) is an unknown function of z, say $U\alpha(z)$. If one sets $\alpha(z) \equiv 0$, one obtains a Robey-type radiation impedance Z_R which ignores acoustic coupling between the inner and outer squirter surface. The actual radiation impedance Z is obtained by adding to Z_R the transfer impedance Z_α generated by the unknown radial velocity distribution $W\alpha(z)$ across the two semi-infinite cylinders prolonging the squirter proper:

$$Z = Z_R + Z_\alpha \tag{1}$$

The unknown velocity distribution satisfies the integral equation which states the requirement that the pressure field obtained for the outer[6] and inner[11] regions be continuous over the two boundaries $r=a$, $|z| > L$ of these two regions. The effect of a non-vanishing wall thickness h can be approximated by assuming that the thin layer of liquid in the semi-infinite cylindrical shells ($|z| > L$, $a-\frac{1}{2}h < r < a+\frac{1}{2}h$) extending the squirter is radially incompressible.[10] The integral equation thus obtained states that the pressure differential between the inner and outer regions, $p(a-\frac{1}{2}h,z) - p(a+\frac{1}{2}h,z)$, must equal the inertia force exerted by a unit area of liquid shell, i.e. $-i\omega\rho hU\alpha(z)$. Since the integral equation formulation includes non-axisymmetric vibrations,[10] these calculations can be extended to deal with parasitic, e.g. rocking modes of the squirter.

The transfer impedance Z_α can be approximated by means of a variational Rayleigh-Ritz type procedure because Z_α is proportional to a functional which is stationary with respect to the correct solution $\alpha(z)$ of the integral equation.[10] Duncan,[9] however, used a numerical technique to evaluate the squirter impedance. It is these results on which the present study is based.

III. INTERACTION BETWEEN STRUCTURAL (RING) AND ACOUSTIC (SQUIRTER) RESONANCES*

A. Ring Resonances

The *in vacuo* circular natural frequency of a ring or cylindrical shell of aspect ratio $L/a \leq 1.2$ is[12]

$$\omega_{nv} = c_t/a \tag{2}$$

Here, c_t is the bar velocity of the transducer material,

$$c_t = (E/\rho_t)^{\frac{1}{2}}$$

E is the Young's modulus and ρ_t the effective density of the material. This density accounts for extraneous masses, e.g. windings, which contribute to the kinetic energy of the vibrating transducer and thus decrease the natural frequency. The natural frequency can also be lowered by inertia elements introduced specifically to achieve a prescribed lower natural frequency without increasing the squirter radius. This procedure, which consists in attaching axially oriented wedges to the shell or ring, is described in a number of patents.[13,14,15]

The motional impedance *in vacuo* can be written in terms of the natural frequency and of the mass $hA\rho_t$ of the transducer:

$$Z_t = - i\omega hA\rho_t \; [1- (\omega_{nv}/\omega)^2] \tag{3}$$

where

$$A = 4 \pi a L.$$

The impedance in Eq. 3 is purely reactive. The neglect of damping is usually acceptable if one considers submerged, i.e. radiation-damped squirters. A situation where structural damping must be introduced arises when studying squirters driven at their ring resonance, for aspect ratios $L/a \leq 10^{-1}$, i.e., when the radiation resistance is extremely small.[9] This situation is handled by introducing an effective structural resistance ratio (see Eq. 13).

*In Merriweather's nomenclature, Ref. 3.

When the transducer is submerged the transducer impedance Z_t combines with the radiation impedance Z_r to yield the resultant impedance of the submerged squirter:

$$Z = Z_t + Z_r \tag{4}$$

The radiation impedance is expressed conveniently in terms of dimensionless acoustic impedance ratios θ and χ

$$Z_r = A\,\rho c\,(\theta + i\chi) \tag{5}$$

There is, admittedly, an inconsistency in combining radiation impedances computed for $h \approx 0$ with transducer impedances based necessarily on squirters of finite thickness (specifically, $h = 0.2a$). The resulting error tends to boost the bandwidth and to shift the natural frequency of the submerged transducer. The ring resonance of the submerged transducer is identified here with the frequency for which the reactive component of Eq. 4 vanishes

$$\mathcal{I}m Z \equiv X_t + X_r = 0 \quad , \quad \text{for } \omega = \omega_n \tag{6}$$

It is convenient to write the impedance in the dimensionless form of an impedance ratio. For this purpose the frequency ω is expressed in terms of the acoustic wave number k and of the radius a. It is noted that the dimensionless <u>in vacuo</u> ring resonance $(ka)_{nv}$ corresponding to Eq. 2 simply equals the velocity ratio, c_t/c. Combining Eqs. 4 and 5 the impedance ratio of the submerged transducer becomes

$$\frac{Z}{A\rho c} = \theta + i\left[\frac{h}{a}\,\frac{\rho_t}{\rho}\left(\frac{c_t^2}{c^2}\,\frac{1}{ka} - ka\right) + \chi\right] \tag{7}$$

The dimensionless natural frequency of the submerged shell is obtained by setting the reactive component in Eq. 7 equal to zero:

$$(ka)_n = \frac{c_t}{c}\left(1 - \frac{\rho}{\rho_t}\,\frac{a}{h}\,\frac{\chi}{ka}\bigg|_{ka=(ka)_n}\right)^{-\frac{1}{2}} \tag{8}$$

In our convention a massive reactance is negative, thus reducing the natural frequency of the submerged transducer below its <u>in vacuo</u> value. For $kL < 1$

the ratio χ/ka in Eq. 8 is a negative constant thus permitting a straightforward calculation of the natural frequency from the transducer parameters and from the χ vs. ka curves in Ref. 9. With increasing kL the ratio $|\chi|/ka$ decreases. In fact, the slope $\partial|\chi|/\partial(ka)$ becomes negative. For large enough aspectratio L/a, χ will go through zero and become a stiffness with increasing ka. Under these conditions there exists the possibility that several resonances may occur. Specifically, as ka increases, the resulting increase of the kinetic energy stored in the shell can compensate the decrease in fluid kinetic energy resulting from the negative slope of $|\chi|$ vs. frequency. Thus, if χ=0 for ka= c_t/c, the shell will resonate at the same frequency in water and <u>in vacuo</u>. As the frequency increases further and χ becomes stiffness-like, the submerged shell can display higher natural frequencies submerged than <u>in vacuo</u>. In fact, there may be an entire frequency band where a near-resonant condition prevails.

For c_t/c relatively small (equal to 2 as opposed to the value of 3 more typical of transducer material) two, and eventually three resonances are encountered as L/a is increased. The natural frequencies were computed for two values of c_t/c, as a function of L/a, for a thickness-to-radius ratio h/a = 0.2, and for the specific gravity of Barium Titanate (ρ_t/ρ = 5.36). For the larger value of c_t/c (Fig. 2) the ring resonance drops below its <u>in vacuo</u> value of three to a minimum, and eventually rises back to its <u>in vacuo</u> value. For c_t/c = 2 the ring resonance again starts with its <u>in vacuo</u> value. Additional resonances make their appearance (Fig. 3), one of them tending to the <u>in vacuo</u> ring resonance from above as L/a is increased.

B. <u>The Squirter Resonances</u>

The squirter resonance corresponds to a maximum in the curve of the radiation resistance vs. frequency. It tends to lie near the organ pipe resonances at which the liquid column inside the squirter measures an odd number of half acoustic wavelengths,

$$(ka)_r \approx \frac{(2n-1)\pi}{2L/a}, \qquad n=1, 2... \tag{9}$$

Because of the end correction, the observed squirter resonance occurs at somewhat lower frequencies. Merriweather[3] gives an empirical equation fitting

his experimental squirter resonances:

$$(ka)_r = \frac{(2n-1)\pi}{2.514(L/a) + 1.052}$$

This equation generates frequencies which are in fair agreement with the squirter resonances computed from Duncan's theoretical results (Figs. 2 and 3). The bandwidth of the resistance peak centered on $ka=(ka)_r$ decreases with increasing L/a, while the peak value of the resistance increases.

We are now in a position to evaluate the performance of a squirter as a function of L/a.

IV. POWER AND BANDWIDTH

A. The Conductance

For a given excitation the acoustic power level is proportional to the conductance defined as the real component of the admittance Z^{-1}. In terms of the impedance components in Eq. 2 the conductance can be written explicitly as

$$\begin{aligned} \Re Z^{-1} &= \Re Z^*/ Z^2 \\ &= R_r/[R_r^2 + (X_t + X_r)^2] \end{aligned} \tag{10}$$

If dimensionless impedance ratios, rather than mechanical impedances are used, the conductance ratio becomes

$$\begin{aligned} \Re \frac{A\rho c}{Z} &= \frac{A\rho c\ R_r}{|z|^2} \\ &= \frac{\theta}{\theta^2+[\chi + \frac{h}{a}\frac{\rho_t}{\rho}(\frac{c_t^2}{c^2}\frac{1}{ka} - ka)]^2} \end{aligned} \tag{11}$$

A low level of θ is thus associated with small conductances, except at the ring resonance of the submerged transducer. At this frequency the conductance ratio reduces to

$$\Re \frac{A\rho c}{Z} = \theta^{-1} \quad , \quad ka = (ka)_n \tag{12}$$

The conclusion that a small θ produces a large conductance at the ring resonance is valid provided the acoustic resistance ratio is significantly larger than the effective structural resistance ratio θ_t of the transducer. If this is not the case, specifically for the low values of θ predicted in Ref. 9 for small aspect ratios L/a, Eq. 12 becomes

$$\Re \frac{A\rho c}{Z} = \frac{\theta}{\vartheta_t^2} \quad . \quad ka = (ka)_n, \ \theta \ll \theta_t^2 \tag{13}$$

The extremely low levels of θ predicted in Ref. 9 for $L/a \leq 10^{-1}$ correspond to this situation.

B. Power Level and Bandwidth

It has generally been assumed that it is desirable to make the squirter resonance and the submerged ring resonance coincide, i.e. in the present notation, to make $(ka)_n = (ka)_r$ (see, for example, Ref. 3, p. 24: "The ideal arrangement for utilization of the squirter modes would be to choose a length-to-radius ratio such that the squirter and radius ratio coincide.") The corresponding conductance ratio is obtained by setting $\theta = \theta_{max}$ in Eq. 12:

$$\Re \frac{A\rho c}{Z} = (\theta_{max})^{-1} \quad , \quad ka = (ka)_n = (ka)_r \tag{14}$$

If the peak value θ_{max} is large, i.e. for long squirters ($L/a \geq 3/4$), this coincidence of ring and squirter resonances is only a desirable situation provided certain other conditions, to be derived below, are satisfied. This conclusion is borne out by the plots of conductance ratios for L/a = 0.8 in Figs. 4 and 5. For $c_t/c = 3$ (Fig. 4), there is a single ring resonance $ka = (ka)_n$ which gives rise to a conductance maximum corresponding to Eq. 12. For the larger of the two squirter ratios in Fig. 4, a secondary conductance maximum occurs in the vicinity of the squirter resonance $ka = (ka)_r$. However, θ_{max} is so large that the corresponding conductance is relatively small and does not correspond to a peak. For $c_t/c = 2$ (Fig. 5), at least one ring resonance occurs below the squirter resonance. Once again, the large value of θ_{max} achieved for the larger aspect ratio depresses the conductance curve near $ka \approx (ka)_r$. In fact, this combination of c_t/c and of L/a was selected to make the middle of the three ring resonances coincide exactly with the squirter

resonance. This particular combination of parameters illustrates the situation discussed in Sec. III.a, whereby a near-resonant condition exists over a wide frequency range. It thus appears feasible to adjust the parameters of a squirter of large-aspect ratio so as to extend its bandwidth over a wide near-resonant frequency range encompassing several structural resonances. The requirement is that

$$\chi = 0 \quad \text{for } ka \approx c_t/c \tag{15}$$

and

$$\frac{\partial X_t}{\partial(ka)} = - \frac{\partial X_r}{\partial(ka)} \quad , ka \approx c_t/c \tag{16}$$

or, using Eq. 7

$$\frac{h}{a} \frac{\rho_t}{\rho} \left(\frac{c_t^2}{c^2} \frac{1}{(ka)^2} + 1 \right) \approx \frac{\partial}{\partial(ka)} \quad , ka \approx c_t/c \tag{17}$$

If Eq. 15 is satisfied, $(ka)_n \approx (ka)_r$. Hence, even though coincidence of squirter and ring resonance locally depresses the conductance vs. frequency curve, a frequency range of high conductance can be achieved if Eqs. 16 and 17 are satisfied. Because of the error in radiation reactance resulting from the assumption of vanishing wall thickness, we did not attempt to select transducer parameters satisfying Eq. 17 exactly.

C. Conclusions

The conductance maxima, the frequency at which they occur, and their bandwidth are tabulated below for the two squirter aspect ratios covered in Figs. 4 and 5. Once again the squirter of small aspect ratio is not included, because its peak conductance level and bandwidth are determined by its unpredictable structural losses, and because its low conductance level makes it an undesirable design.

The conclusions drawn from this study can now be summarized:

1. Short squirters ($L/a \leq 0.1$) are undesirable because they are characterized by a generally low conductance level resulting from their extremely low radiation resistance. Even in the unrealistic case of a short squirter whose structural losses are comparable to or smaller than its small radiation damping,

the conductance peak associated with the ring resonance is high, but the bandwidth is impractically narrow.

2. Squirters of medium aspect ratio ($L/a \approx 0.36$) and large aspect ratio ($L/a \approx 0.80$) can combine high conductance levels with wide bandwidths provided the ring natural frequencies are properly selected: the medium aspect ratio is suitable for a squirter of high <u>in vacuo</u> ring natural frequency ($c_t/c \approx 3$), while the large aspect ratio is more desirable when associated with a relatively small <u>in vacuo</u> ring natural frequency ($c_t/c \approx 2$). The introduction of inertia masses to lower the <u>in vacuo</u> natural frequencies[13,14,15] provides a means of adjusting this frequency.

3. A squirter of large aspect ratio whose structural (ring) resonance coincides with its squirter (acoustic) resonance produces a wide bandwidth, provided the frequency derivatives of the radiation and transducer reactances satisfy certain conditions. Specifically, the transducer parameters must be selected to satisfy Eq. 17, thus causing the variations, with frequency, of the transducer and fluid reactances to mutually compensate over a frequency range where near-resonant conditions will thus be achieved.

Table

Maximum Conductance Ratio Level, Corresponding Dimensionless Frequency, and Bandwidth

<table>
<tr><th>L/a \ c_t/c</th><th colspan="2">2</th><th>3</th><th></th></tr>
<tr><td rowspan="3">0.36</td><td colspan="2">6.9 dB</td><td>-0.2 dB</td><td>Maximum Conductance Ratio Level</td></tr>
<tr><td colspan="2">1.5</td><td>2.5</td><td>ka of Maximum Conductance</td></tr>
<tr><td colspan="2">8%</td><td>31%</td><td>-3 dB Bandwidth</td></tr>
<tr><td rowspan="3">0.8</td><td>.3 dB</td><td>-1.9 dB</td><td>-.5 dB</td><td>Maximum Conductance Ratio Level</td></tr>
<tr><td>1.0</td><td>2.1</td><td>2.8</td><td>ka of Maximum Conductance</td></tr>
<tr><td>13%</td><td>54%</td><td>23%</td><td>-3 dB Bandwidth</td></tr>
</table>

The combination of acoustic impedances computed for squirters of vanishing wall thickness with the structural impedances of squirters of finite wall thickness ($h/a = 0.2$) necessarily makes these conclusions qualitative rather than quantitative. Furthermore, to find a truly optimal combination of L/a and c_t/c for a specified center frequency and minimum bandwidth and conductance level requirements necessitates the evaluation of a sufficient number of combinations of aspect ratio and dimensionless *in vacuo* natural frequencies to permit the plotting of families of design curves. The present results do however indicate that the computation of such curves is feasible, while the procedure described in Ref. 9 indicates how the required radiation loading curves can be computed.

Acknowledgment

My colleague, Stephen C. Orr, performed the calculations on which Figs. 2, 3, 4 and 5 are based.

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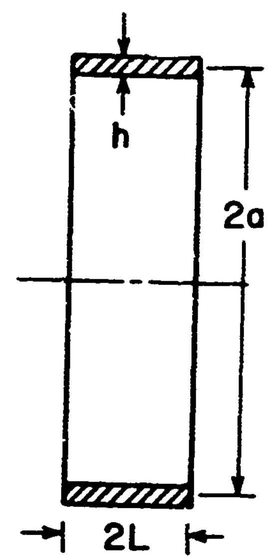

Fig. 1. Geometry of free-flooding cylindrical transducer.

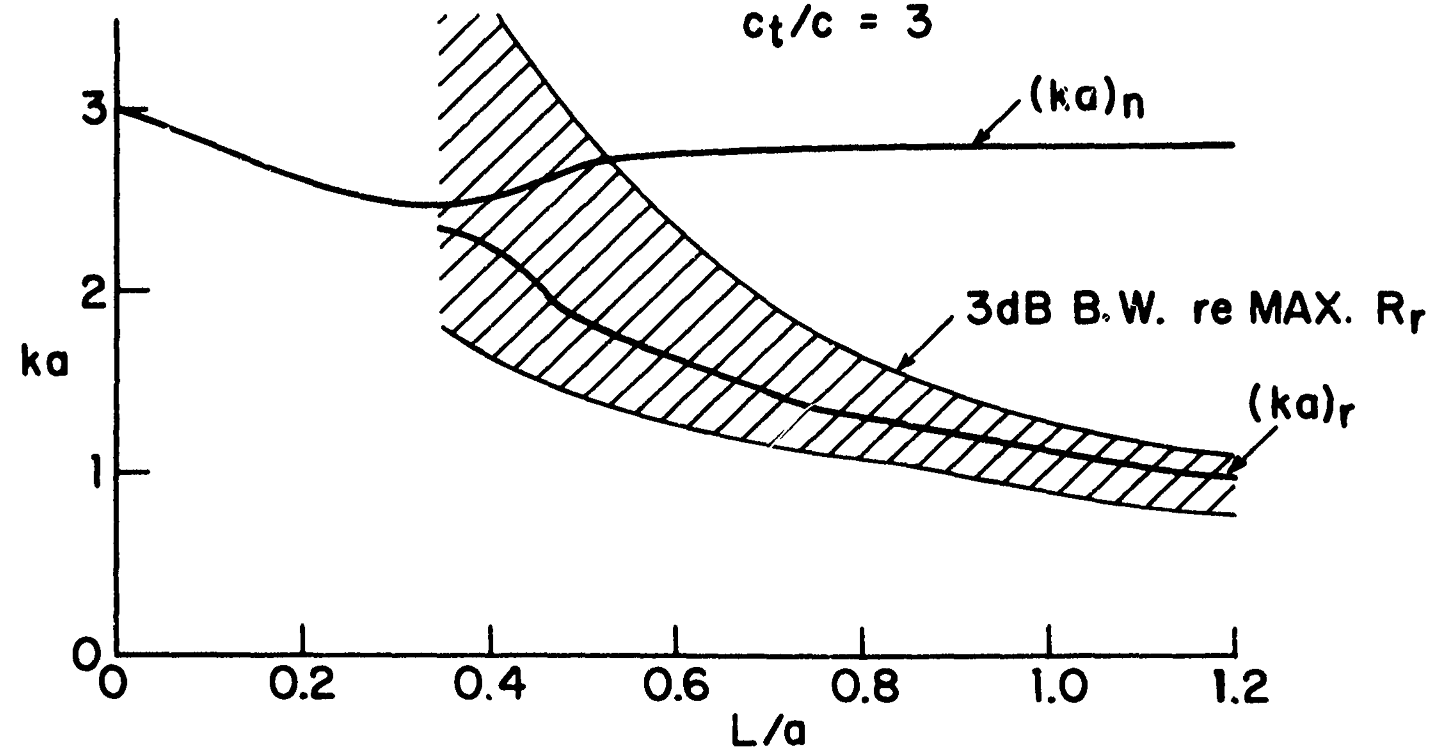

Fig. 2. Dimensionless natural frequencies of radially vibrating submerged free-flooding cylinder $(ka)_n$, and dimensionless squirter resonances $(ka)_r$ defined as frequencies of peak radiation resistance, B.W. ≡ bandwidth of radiation resistance peak between -3 dB points. <u>In vacuo</u> dimensionless natural frequency: $(ka)_{nv} = c_t/c = 3$.

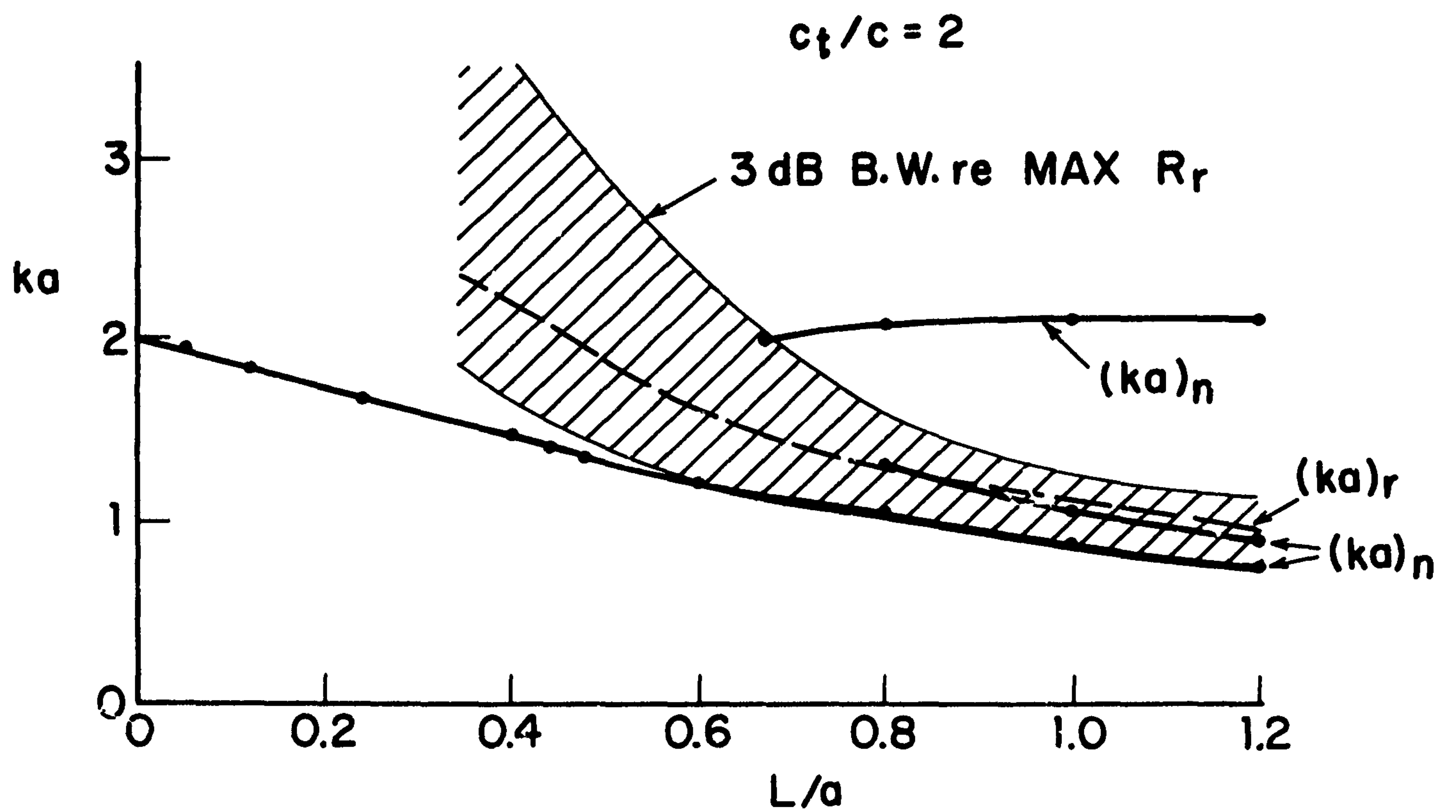

Fig. 3. Same as Fig. 2, for <u>in vacuo</u> dimensionless natural frequency $(ka)_{nv} = c_t/c = 2$.

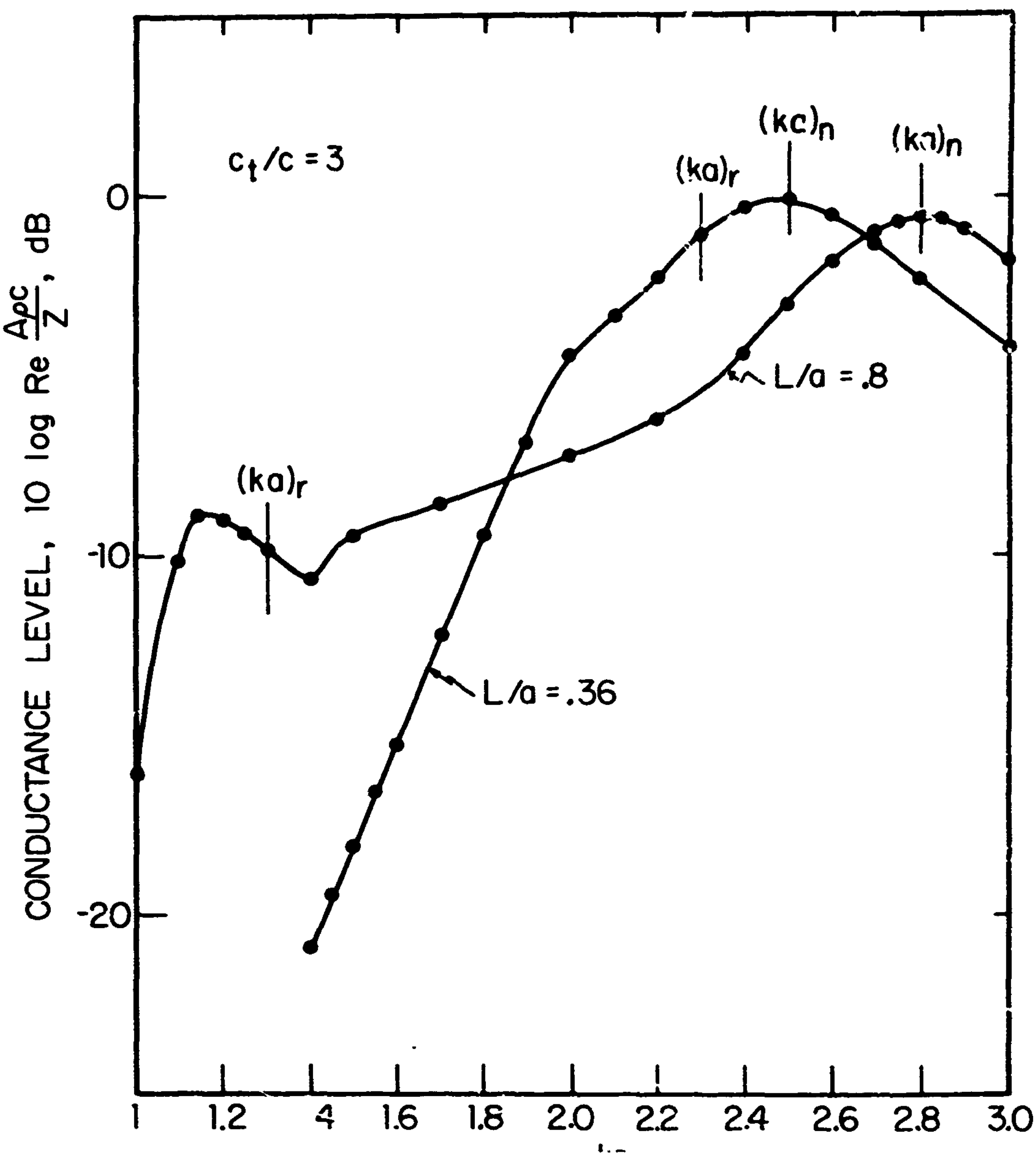

Fig. 4. Conductance ratio (dimensionless), defined as the motional conductance multiplied by $A\rho c$. In vacuo dimensionless natural frequency: $(ka)_{nv} = c_t/c = 3$. (Curve interpolated between calculated points indicated.)

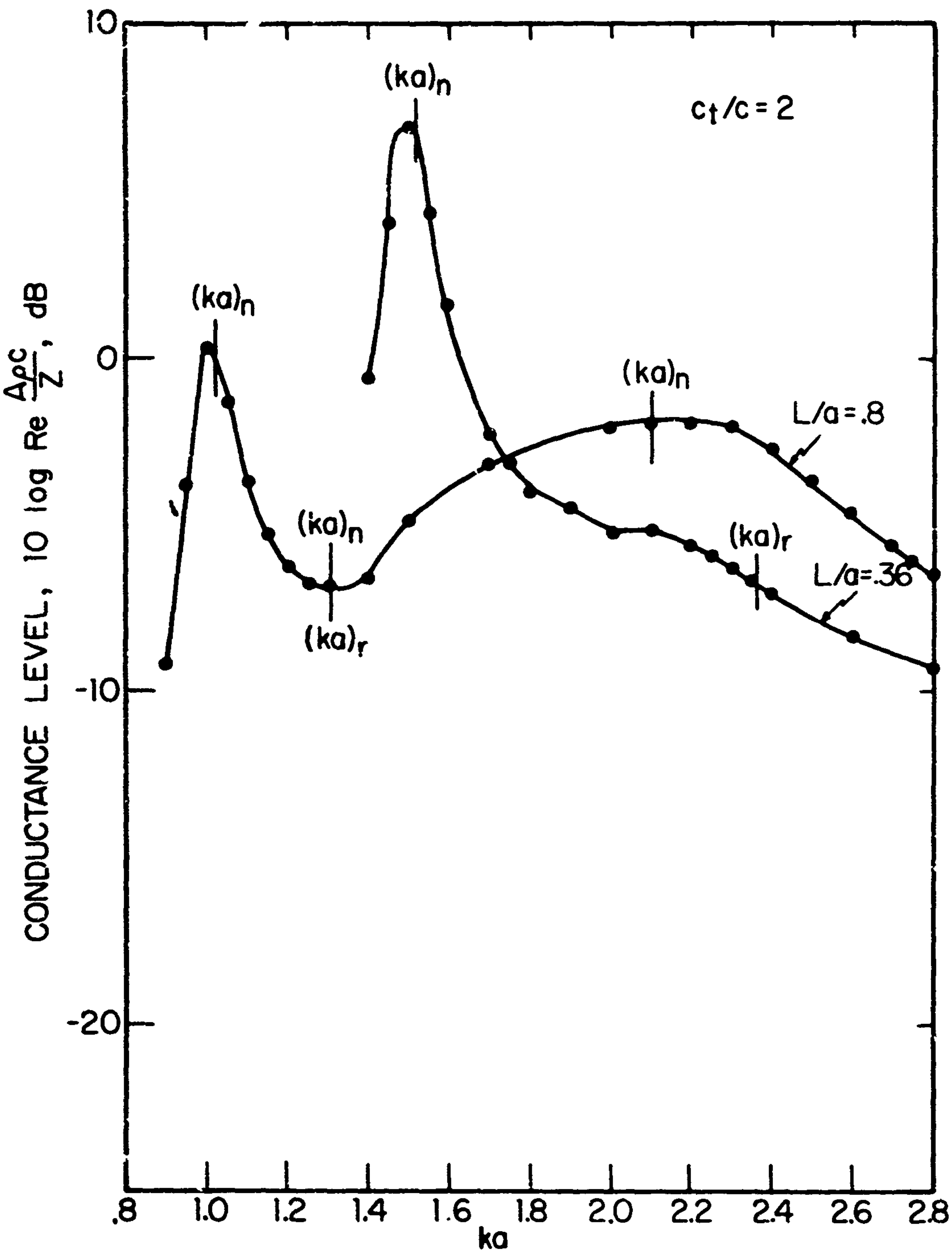

Fig. 5. Same as Fig. 4, for <u>in vacuo</u> dimensionless natural frequency $(ka)_{nv} = c_t/c = 2$.

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11. SUPPLEMENTARY NOTES --------------	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Acoustics Programs Naval Applications and Analysis Division

13. ABSTRACT

The free-flooding cylindrical transducer devoid of pressure-release material combines resistance to hydrostatic pressure with design flexibility resulting from the existence of resonances primarily controlled by two independent dimensions: the radius, which controls the structural (ring) resonance, and the axial length which determines the acoustic ("squirter") resonance. Values of radiation impedance generated for a squirter of vanishing wall thickness from an integral equation formulation of the free-flooding cylinder of finite length, were used to compute curves of dimensionless natural frequency vs. squirter aspect ratio (ratio of length to diameter) and of motional conductance vs. dimensionless frequency. It is concluded that (a) squirters of small aspect ratio are undesirable, (b) squirters of medium and large aspect ratio can combine wide bandwidths with substantial conductance levels; (c) squirters with large aspect ratios should have in vacuo natural frequencies substantially lower than generally obtained with transducer materials; the natural frequency can be lowered to the desired value by attaching axially oriented inertia wedges to the squirter; (d) near-coincidence of the acoustical (squirter) resonance with the structural (ring) resonance can produce an exceptionally wide bandwidth for squirters of large aspect ratio provided the slopes of the transducer and radiation reactance mutually compensate near the in vacuo natural frequency, thus producing a frequency range of near-resonant condition. An equation is derived which the transducer parameters must satisfy to produce this condition.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Sonar Transducers						
Underwater Sound Sources						
2. Impedance						
Acoustic Impedance						

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